BIOLOGICALLY INSPIRED TOYS USING ARTIFICIAL MUSCLES

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Many of us know bionics as the instrument that propelled Col. Steve Austin, the astronaut who was „rebuilt" after a crash, on a TV show over twenty years ago. With bionic muscles, the character was capable of strength and speeds that are far superior to human. Recent development in electroactive polymers, so-called artificial muscles, could one day be used to make such bionics possible. Meanwhile, as this technology evolves novel mechanisms are expected to emerge that are biologically inspired. Making toys and interactive games using these materials offer many exciting new possibilities.

INTRODUCTION

Creating toys that mimic the shape and performance of biological creatures has always been a highly desired objective of developers of toys. Visiting toy stores easily reveals how far we have come in imitating biology, where frogs swimming in a fish bawl, dog walking back and forth on the floor and possibly even barking are part of stores display. Operating toys that simulate the functions and performance of human or animals involved the introduction of various actuation mechanisms that evolved with the advancement in technology. Upper end toys are becoming increasingly sophisticated, operating autonomously, wirelessly programmable with such functions as walking, talking, and making expressions and exhibiting behavior that imitate human and animals. In spite of the success there is still a large gap between the performance of toys and biological creatures. Recent emergence of electroactive polymers (EAP) may finally enable the bridging of the gap in performance [Bar-Cohen, 2001, http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi-books.htm]. These materials have functional similarity to biological muscles, including resilience, damage tolerance, and large actuation strains (stretching, contracting or bending), earning them the moniker Artificial Muscle.

EAP may be used to eliminate the need for gears, bearings, and other elements that complicate the construction of toys. Visco-elastic EAP materials could provide more lifelike aesthetics, vibration and shock dampening, and more flexible actuator configurations. Moreover, multiple studies have shown that the visco-elastic properties of animal tissue are key to locomotion and general stability. In many cases, a passive "skin" like material is used and exploiting the properties of artificial muscles may enable the movement of the covering skin, to define the character of the toy and provide expressivity. Such robots or digitally rendered creature that simulate organisms have been used in many movies including *A Bug's Life*, *Deep Blue Sea*, *The Matrix*, and *Mighty Joe Young* [Chapter 16, Hanson and Pioggia, http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi-books.htm].

For many years, the field of EAP has received relatively little attention since the number of available materials and their actuation capability were limited. The change in this view occurred in the last ten years, as a result of the development of new EAP materials that respond to electrical stimulation with large displacement. Generally, EAPs can induce strains that are as high as two orders of magnitude greater than the striction-limited, rigid and fragile electroactive ceramics (EAC). Further, EAP materials are superior to shape memory alloys (SMA) in higher response speed, lower density, and greater resilience. These materials are highly attractive for the potential of making biologically-inspired robots and toys however they are still not available commercially and their robustness needs further enhancement. Researchers have already demonstrated a series of novel applications for these materials including catheter steering element, robotic arm, gripper, loudspeaker, active diaphragm, and dust-wiper. Some of the interesting applications that are currently being considered include a smart-bra that allow battery driven shape control of clothing. The capability of EAPs to emulate muscles offers robotic capabilities that have been in the realm of science fiction when relying on existing actuation materials. The large displacement that can be obtained using low mass, low power and, in some of the EAPs, also low voltage, makes them attractive actuators that are agile, damage tolerant, noiseless, lightweight, mass producible, and inexpensive. Combining the bending and longitudinal strain capabilities of EAP actuators, a miniature robotic arm was designed and constructed at JPL (see Figure 1 and 2). This robotic arm illustrates some of the unique capability of EAP. It consisted of four bending type EAP finger strips with hooks at the bottom emulating fingernails and it is grabbing a rock similar to human hand. The author is seeking to stimulate the development of niche applications for EAP becoming actuators-of-choice in spite of the technology challenges and limitations.

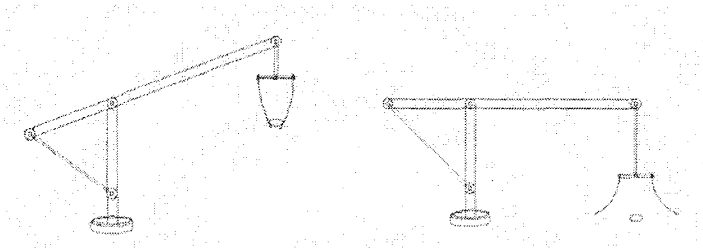

FIGURE: 1: Simulated view of a robotic arm taking advantage of the capability of longitudinal and bending EAP actuators.

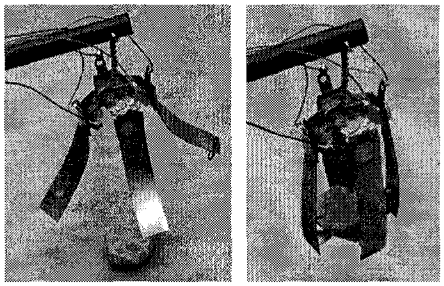

FIGURE 2: 4-finger EAP gripper lifting a rock.

In recognition of the need for international cooperation among the developers, users, and potential sponsors, the author organized the first EAP Conference on March 1-2, 1999, though SPIE International as part of the Smart Structures and Materials Symposium [http://www.spie.org/web/meetings/programs/ss99/confs/3669.html]. This conference was held in Newport Beach, California, USA and was the largest ever on this subject, marking an important milestone and turning the spotlight onto these emerging materials and their potential. This SPIE conference is now organized annually and has been steadily growing in number of presentations and attendees. Following this success, a Materials Research Society (MRS) conference was initiated to address fundamental issues related to the material science of EAP [http://www.mrs.org/meetings/fall99/progbook/ProgramBookFF.html]. Currently, there is a website that archives related information and links to homepages of EAP research and development facilities worldwide [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm], and a semi-annual Newsletter is issued electronically [http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html].

The increased resources, the growing number of investigators conducting research related to EAP, and the improved collaboration among developers, users, and sponsors are expected to lead to rapid progress in the coming years. In 1999, the author posted a challenge to the worldwide community of EAP experts to develop a robotic arm that is actuated by artificial muscles to win an arm wrestling match with a human opponent (Figure 3). Progress towards this goal will lead to great benefits, particularly in the medical area, including effective prosthetics. Decades from now, EAP may be used to replace damaged human muscles, potentially leading to a "bionic human." A remarkable contribution of the EAP field would be to one day see a handicapped person jogging to the grocery store using this technology.

FIGURE 3: Grand challenge for the development of EAP actuated robotics

HISTORICAL REVIEW AND CURRENTLY AVAILABLE ACTIVE POLYMERS

The beginning of the field of EAP can be traced back to an 1880 experiment that was conducted by Roentgen using a rubber-band that was charged and discharged with fixed end and a mass attached to the free end [Roentgen, 1880]. Sacerdote [1899] followed this experiment with a formulation of the strain response to electric field activation. Further milestone progress was recorded only in 1925 with the discovery of a piezoelectric polymer called electret when carnauba wax, rosin, and beeswax were solidified by cooling while subjected to a DC bias field [Eguchi, 1925]. Generally, there are many polymers that exhibit volume or shape change in response to perturbation of the balance between repulsive intermolecular forces that act to expand the polymer network and attractive forces that act to shrink it. Repulsive forces are usually electrostatic or hydrophobic in nature, whereas attraction is mediated by hydrogen bonding or van der Waals interactions. The competition between these counteracting forces, and hence the volume or shape change, can thus be controlled by subtle changes in parameters such as solvent or gel composition, temperature, pH, light, etc. The type of polymers that can be activated by non-electrical means include: Chemically Activated, Shape Memory Polymers, Inflatable Structures, including McKibben Muscle, Light Activated Polymers, Magnetically Activated Polymers, and Thermally Activated Gels [Chapter 1, http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi-books.htm].

Polymers that are chemically stimulated were discovered over half-a-century ago when collagen filaments were demonstrated to reversibly contract or expand when dipped in acid or alkali aqueous solutions, respectively [Katchalsky, 1949]. Even though relatively little has since been done to exploit such 'chemo-mechanical' actuators, this early work pioneered the development of synthetic polymers that mimic biological muscles. The convenience and practicality of electrical stimulation, and technology progress led to a growing interest in EAP materials. Following the 1969 observation of a substantial piezoelectric activity in PVF2 [http://www.ndt.net/article/yosi/yosi.htm], investigators started to examine other polymer systems, and a series of effective materials have emerged. The largest progress in EAP materials development has occurred in the last ten years where effective materials that can induce strains that exceed 300% have emerged [Chapter 16, Kornbluh, et al, http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-book_outline.htm].

EAP can be divided into two major categories based on their activation mechanism including: ionic and electronic (Table 1). The electronic polymers (electrostrictive, electrostatic, piezoelectric, and ferroelectric) can be made to hold the induced displacement under activation of a DC voltage, allowing them to be considered for robotic applications. Also, these materials have a greater mechanical energy density and they can be operated in air with no major constraints. However, they require a high activation fields (>100-V/μm) that is close to the breakdown level. In contrast, ionic EAP materials (gels, polymer-metal composites, conductive polymers, and carbon nanotubes.) require drive voltages as low as 1-2 Volts. The disadvantages of these materials are the need to maintain their wetness, and it is difficult to sustain DC-induced displacements (except for conductive polymers). The induced displacement of both the electronic and ionic EAP can be geometrically designed to bend, stretch or contract. Any of the existing EAP materials can be made to bend with a significant curving response, offering actuators with an easy to see reaction and an appealing response. However, bending actuators have relatively limited applications due to the low force or torque that can be induced.

TABLE 1: Example of EAP materials

Electronic EAP

- Dielectric EAP
- Electrostrictive Graft Elastomers
- Electrostrictive Paper
- Electro-Viscoelastic Elastomers
- Liquid Crystal Elastomers (LCE)
- Ferroelectric Polymers

Ionic EAP

- Carbon Nanotubes (CNT)
- Conductive Polymers (CP)
- ElectroRheological Fluids (ERF)
- Ionic Polymer Gels (IPG)
- Ionic Polymer Metallic Composite (IPMC)

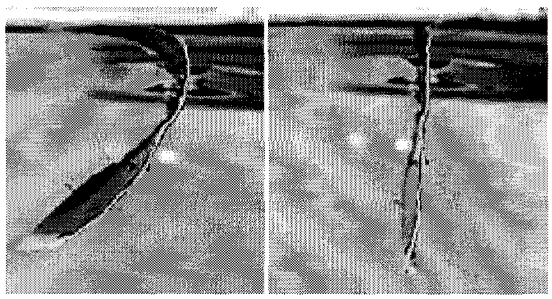

FIGURE 4: Conductive EAP actuator is shown bending under stimulation of 2-V, 50-A.

TABLE 2: A Summary of the advantages and disadvantages of the two basic EAP groups

EAP type	Advantages	Disadvantages
Electronic EAP	• Long life in room conditions • Rapid response (mSec levels) • Can hold strain under DC activation • Induces relatively large actuation forces	• Requires high voltages (>100 MV/m) • Requires compromise between strain and stress • Glass transition temperature is inadequate for low temperature actuation tasks
Ionic EAP	• Provides mostly bending actuation (longitudinal mechanisms can be constructed) • Large bending displacements • Requires low voltage	• Except for CPs, ionic EAPs do not hold strain under DC voltage • Slow response (fraction of a second) • Bending EAPs induce a relatively low actuation force • Except for CPs, it is difficult to produce a consistent material (particularly IPMC) • In aqueous systems the material sustains hydrolysis at >1.23-V

MAKING TOYS ACTUATED BY EAP

EAP are offering attractive characteristics with the potential to produce more realistic models of living creatures at significantly lower cost. Mimicking nature would immensely expand the collection and functionality of the toys that are currently available for children. Such toys will be able to perform tasks that are impossible with existing capabilities. As this technology evolves, biologically inspired toys actuated by EAP materials emulating biological creatures are expected to emerge. One of the issues that can limit the selection of EAP actuators is the upper voltage limit that is generally being considered safe for use in toys. The current level that is being used is below 24-V and this limit constrains the consideration of the electronic-EAP actuators, which may have greater technology readiness than the ionic types.

To promote the development of effective EAP actuators, two platforms were developed that include an android head that can make facial expressions and a robotic hand with activatable joints. The android head was developed by the University of Pisa, Italy, and it is intended to replicate human facial expressions [Figure 4, and video on http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm]. At present, conventional electric motors are producing the required deformations required to make the relevant facial expressions. Data is acquired, stored in a personal computer, and analyzed through a dedicated neural network. Human expressions can be acquired by a digital camcorder in the form of motion capture sequences and be imitated by the android. Once effective EAP materials are chosen, they will be modeled into the control system in terms of surface shape modifications and control instructions for the creation of the desired facial expressions. The robotic hand, which was developed at Sheffield Hallam U., UK [Figure 5 and video on http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm] is equipped with tandems and sensors for the operation of the various joints similar to human hand. One of the fingers of this hand is currently being driven by a conventional motor in order to establish a baseline and it would be substituted by EAP when such materials are developed as effective actuators.

FIGURE 4: An android head (Photographed at JPL) as EAP platform will use such actuators to make facial expressions (Courtesy of G. Pioggia, University of Pisa, Italy).

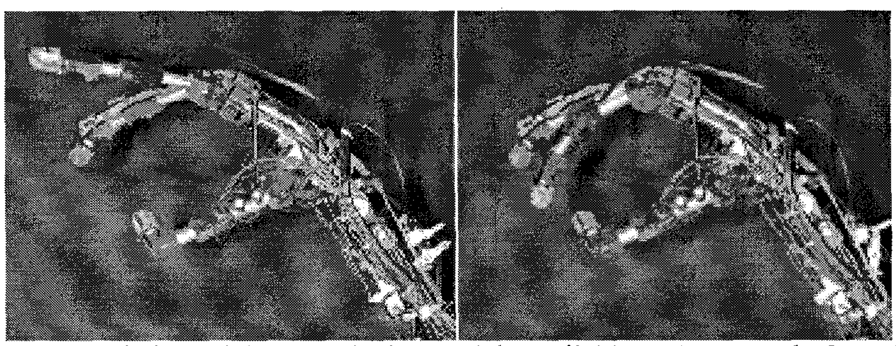

FIGURE 5: Robotic hand (Photographed at JPL) is available at JPL as a platform for demonstration of EAP actuators [Courtesy of Dr. Graham Whiteley, Sheffield Hallam U., UK. The actuators were installed by Giovanni Pioggia – U. of Pisa, Italy/JPL].

The easy capability to produce EAP in various shapes and configurations can be exploited using such methods as ink-jet stereolithography and printing techniques. A polymer can be dissolved in a volatile solvent and ejected drop-by-drop onto various substrates offering the potential of making complete toys driven by EAP actuators in full 3D detail allowing rapid prototyping and quick mass production. Patterns can be introduced in the deposition steps making a fast and inexpensive procedure that is independent of the polymer. Further, 3D structures can be constructed by depositing different layers of polymer without damaging the underlying structures as commonly occurs in spin-coating and solvent casting [chapter 14, Bar-Cohen, et al, http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-book outline.htm].

HAPTIC INTERFACES ALLOWING REMOTE PRESENCE TOYS AND INTERACTIVE GAMES

Toys that are remotely operated as well as interactive computer games that involve virtual reality with the ability to "feel" the remote or virtual environment are highly attractive and offer unmatched capabilities. To address this need, the engineering community has started developing haptic (tactile and force) feedback systems [http://ndeaa.jpl.nasa.gov/nasa-nde/memica/memica.htm]. Users of future computer games may immerse themselves in the display/presentation medium by being connected thru haptic and tactile interfaces to allow them to "feel the action" at the level of their fingers and toes rather than the current large scale capability. At the present time, haptic feedback is a less developed modality of interacting with remote and virtual worlds compared with visual and auditory feedback. Thus, realism especially suffers when remote and virtual tasks involve dexterous manipulation or interaction in visually occluded scenes. Recently, using electroactive polymer liquid called Electrorheological Fluids (ERFs) enabled the potential of such a capability with a very high resolution and large work space. These fluids become highly viscous under electroactivation and a novel haptic concept was developed by JPL and Rutgers University scientist to take advantage of this property. The concept is called MEMICA (remote MEchanical MIrroring using Controlled stiffness and Actuators) [http://ndeaa.jpl.nasa.gov/nasa-nde/memica/memica.htm]. The key aspects of a MEMICA system are miniature Electrically Controlled Stiffness (ECS) elements and Electrically Controlled Force and Stiffness (ECFS) actuators that mirror the stiffness and forces at remote/virtual sites. The ECS elements and ECFS actuators, which make use of ERFs, are integrated on a pair of instrumented gloves. Forces applied at the remote or virtual environment are reflected to the user using this ERF base system where a change in the system viscosity occurs proportionally to the force to be transmitted. The potential use of this system in a surgery simulation of abdominal aortic aneurysms is shown in Figure 6.

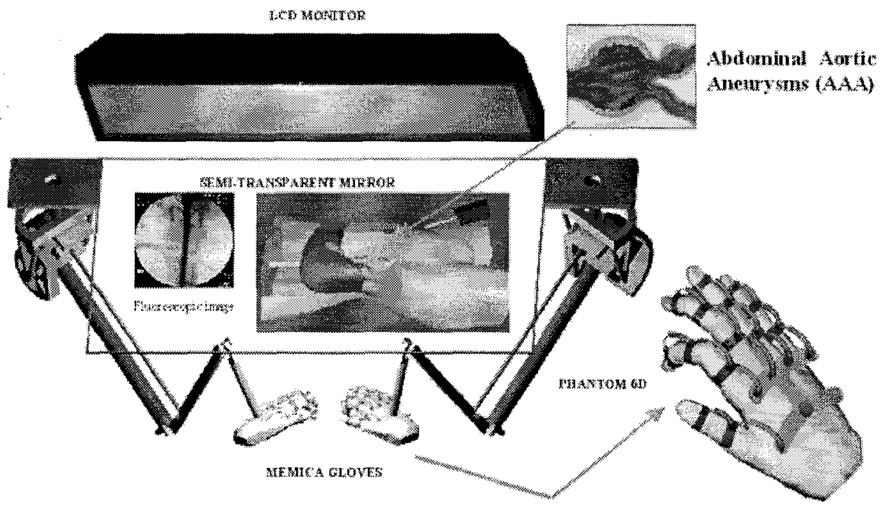

FIGURE 6: Performing Virtual Reality Medical Tasks via the Electro-Rheological Fluid Based MEMICA Haptic Interface offer the potential of highly attractive interactive computer games.

NEED FOR EAP TECHNOLOGY INFRASTRUCTURE

As polymers, EAP materials can be easily formed in various shapes, their properties can be engineered and they can potentially be integrated with micro-electro-mechanical-systems (MEMS) sensors to produce smart actuators. To develop efficient EAP that are robust for practical applications there is a need to establish an adequate EAP infrastructure. This requires developing adequate understanding of EAP materials' behavior, as well as effective processing and characterization techniques. Enhancement of the actuation force requires understanding the basic principles using computational chemistry models, comprehensive material science, electro-mechanics analytical tools and improved material processing techniques. Efforts are needed to gain a better understanding of the parameters that control the EAP electro-activation force and deformation. The processes of synthesizing, fabricating, electroding, shaping and handling will need to be refined to maximize the EAP materials actuation capability and robustness. Methods of reliably characterizing the response of these materials are required to establish database with documented material properties in order to support design engineers considering use of these materials and towards making EAP as actuators of choice. Various configurations of EAP actuators and sensors will need to be studied and modeled to produce an arsenal of effective smart EAP driven system. The development of the infrastructure is a multidisciplinary task and it requires international collaboration.

CONCLUSION

Electroactive polymers have emerged with great potential and enabled the development of unique devices that are biologically inspired. EAP may change future toys, but additional research and development effort will be required. The development of an effective infrastructure for this field is critical to the commercial availability of robust EAP actuators and the emergence of practical applications. In addition to developing better EAP actuation, a discipline of visco-elastic engineering will need to supplant the traditional engineering of rigid structures including control strategies. The challenges are enormous, but the recent trend of international cooperation, the greater visibility of the field and the surge in funding of related research are offering great hope for the future of these exciting new materials. The potential to operate biologically inspired mechanisms driven by EAP as artificial muscles is offering capabilities that are currently considered science fiction. The author's arm-wrestling challenge having a match between EAP-actuated robots and a human opponent highlights the potential of EAP. To assist in the development of effective EAP an Android head and robotic hand were made available to the author to offer them as platforms for the demonstration of internationally developed actuators.

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